LiDAR QA/QC
- Quantitative and Qualitative Assessment Report -

USGS Somerset County, NJ, LiDAR
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Submitted to:
U.S. Geological Survey

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EXECUTIVE SUMMARY

This Somerset County, NJ Light Detection and Ranging (LiDAR) project was to provide high accuracy bare-earth processed, gridded LiDAR data, for approximately 279 square miles of Somerset county west of 74°30' longitude line. The LiDAR data were acquired and processed by Airborne1 in January 2008 and with a repeat mission due to a system malfunction in April 2008. The product is a mass point dataset with an average point spacing of 0.8m projected in UTM Zone 18 North, NAD83 with units in meters. Elevations are expressed as orthometric heights using vertical datum NAVD 88 and utilizing Geoid 03 with vertical units in meters. The data is tiled, stored in LAS format, and LiDAR returns are classified in 4 classes: non-ground/extracted features last pulse (1), bare earth ground features last pulse (2), extracted feature first pulse (3) and ground first pulse (4).

GeoMetrics provided the survey checkpoints for vertical accuracy testing of this data. Dewberry performed vertical accuracy testing and a quality assessment of this data including a completeness check and a qualitative review to ensure accuracy and usability for the needs of the client.

First, based on survey checkpoints, the LiDAR meets the accuracy required for this project (RMSEz Bare Earth: 0.06m compared to the specified 0.15m for accuracy, and Vegetation: 0.10m compared to the specified 0.27m). Using NSSDA standards, this LiDAR dataset was tested 0.114m fundamental vertical accuracy at 95% confidence level, compared to 0.363m for 2ft equivalent contour. The accuracy is based on open terrain RMSEz (0.058m) x 1.9600. No horizontal displacement was detected when compared with reference orthophotos.

Secondly, Dewberry inventoried the files and confirmed that all tiles were delivered in the specified format and correctly geographically projected. We visually inspected 100% the data at a macro level; no remote-sensing data void was found, there were only minor issues that do not impact the overall quality or usability of this data. The cleanliness of the bare earth model was of good quality although slightly noisy due to poor LiDAR penetration in dense vegetation and to overlapping flightlines. Other minor errors were found (such as minor divots, partial building artifacts and aggressive classification) but are not representative of the majority of the data.

Even though there were minor issues that data exhibits good detail overall. The data exceeds the quantitative accuracy requirements and the level of cleanliness for the bare-earth terrain is of satisfactory quality. In essence, the data should meet most user needs.

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LIDAR QA/QC REPORT

1 Introduction

LiDAR technology data gives access to precise elevation measurements at a very high resolution resulting in a detailed definition of the earth's surface topography. Dewberry's role is to provide an independent verification of this data using a vertical accuracy assessment, a completeness validation of the LiDAR mass points, and a qualitative review of the derived bare earth surface.

First, the quantitative analysis addresses the quality of the data based on absolute accuracy of a limited collection of discrete checkpoint survey measurements. Although only a small amount of points are actually tested through the quantitative assessment, there is an increased level of confidence with LiDAR data due to the relative accuracy. This relative accuracy in turn is based on how well one LiDAR point "fits" in comparison to the next contiguous LiDAR measurement as acquisition conditions remain similar from one point to the next.

Then, the completeness verification is conducted at a project scale (files are considered as the entities). It consists of a file inventory and a validation of data format, projection, and georeference conformity. General statistics over all fields are computed per file and analyzed to identify anomalies especially in elevations and LAS classes.

Finally, to fully address the data for overall accuracy and quality, a qualitative review for anomalies and artifacts is conducted at the data level. As no automatic method exists yet, we perform a manual visualization process based on the knowledge of Dewberry's analysts. This includes creating pseudo image products such as 3-dimensional models. By creating multiple images and using overlay techniques, not only can potential errors be found, but we can also find where the data meets and exceeds expectations.

Within this Quality Assurance/Quality Control process, three fundamental questions were addressed:

- Did the LiDAR system perform to specifications?
- Was the data complete?
- Did the ground classification process yield desirable results for the intended bare-earth terrain product?

2 Quality Assurance

2.1 Completeness of LiDAR deliverables

Once the data are acquired and processed, the first step in our review is to inventory the data delivered, to validate the format, projection, georeferencing and verify the range of elevations.

2.1.1 Inventory and location of data

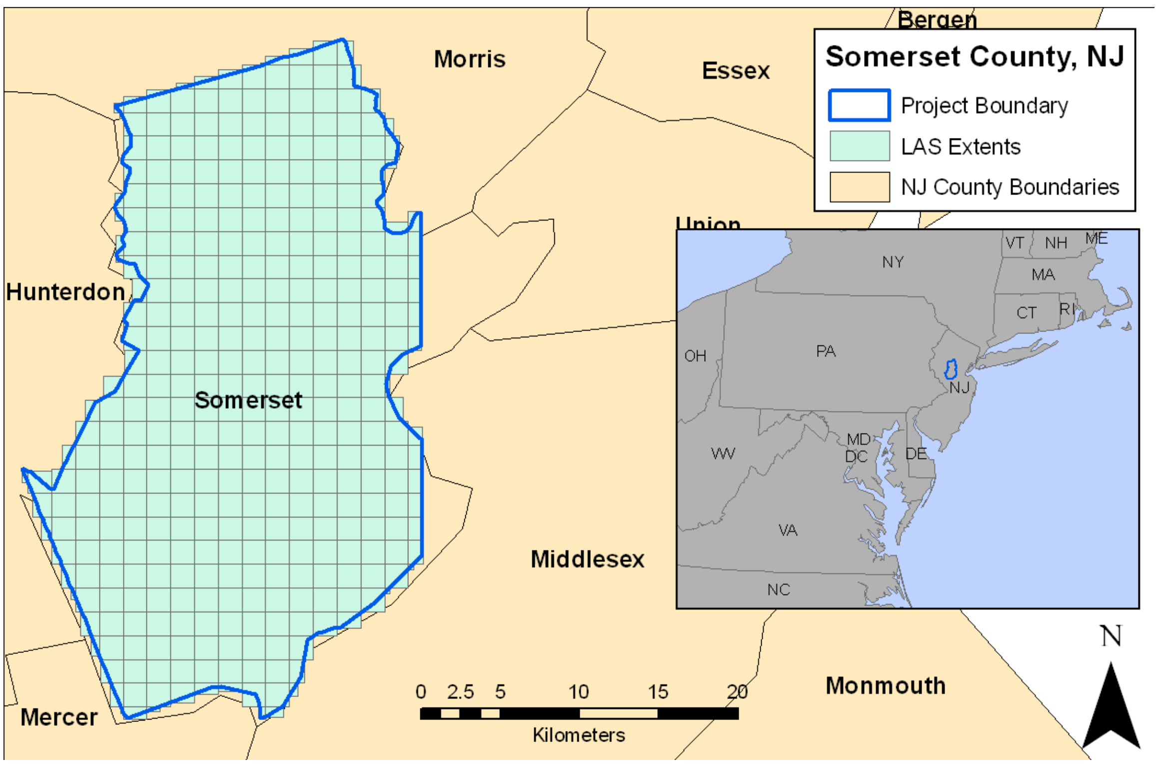


Figure 1 – Delivered LiDAR tiles

The project area is approximately 279 square miles.

A total of 382 tiles were delivered by Airborne1. These tiles follow a large tile scheme and have been trimmed to fit the project boundary.

We have verified that the data is in the correct projection:

- Universal Transverse Mercator, Zone 18 North
- Horizontal Datum: NAD83
- Horizontal Units: Meters
- Vertical Datum: NAVD88 Geoid 03
- Vertical Units: Meters

Data was delivered in one format:

- LAS (extension .las) version 1.1

Airborne1 collected the data using a scanner recording only two pulses: first and last. The points were separated into 4 classes:

- Class 1 is “non-ground/extracted features last pulse” which include noise, buildings and vegetation,
- Class 2 is “ground last pulse” which can be used to define a bare earth model,
- Class 3 is “extracted feature first pulse” which represent the top reflective surface
- Class 4 is “ground first pulse” which is really similar to the ground defined by class 2.

It should be noted that Class 3 and 4 are not ASPRS classes but since this data is a two pulse system, this is the most efficient format to separate the pulses and classification process.

2.1.2 Statistical analysis of tile content

To verify the content of the data and to validate the data integrity, a statistical analysis was performed on all the data. This process allows us to statistically review 100% of the data to identify any gross outliers. This statistical analysis consists of:

1. Extract the header information
2. Read the actual records and compute the number of points, minimum, maximum and mean elevation for each class. Minimum and maximum for other relevant variables are also evaluated.

Each tile was queried to extract the number of LiDAR points and all tiles are within the anticipated size range, except for where fewer points are expected (near the project boundary when the tile was truncated) as illustrated in Figure 2. Another trend is evident on the western side of the data set. There is a line of tiles that has fewer points because of an issue with the synchronization of the IMU and the GPS. The flight lines for this area run North-South and on one of the passes the IMU and GPS were not synchronized. This was caused by an issue between the GPS and IMU when GPS rollover time occurs. When the GPS seconds of the week (SOW) starts back to zero at midnight Saturday night, the IMU timing becomes misaligned as it is expecting the time to continue. This causes a misalignment between the two platforms. The company flying realigned the IMU and GPS in the air; but one flightline had to be removed and was partially reflown where slivers were present. For the most part, the overlap between adjacent flighlines was enough to cover for the missing flightline but causes the row of tiles to have fewer points than the others. This problem is compounded by the presence of a water feature in these tiles.

Figure 3 and Figure 4 both contain normal ranges for the elevation in this region. The lowest z value recorded is in the Southeast corner of Somerset County. There are several mining operation in this area and the bottom of the mine was -4 meters in elevation (see Figure 5).

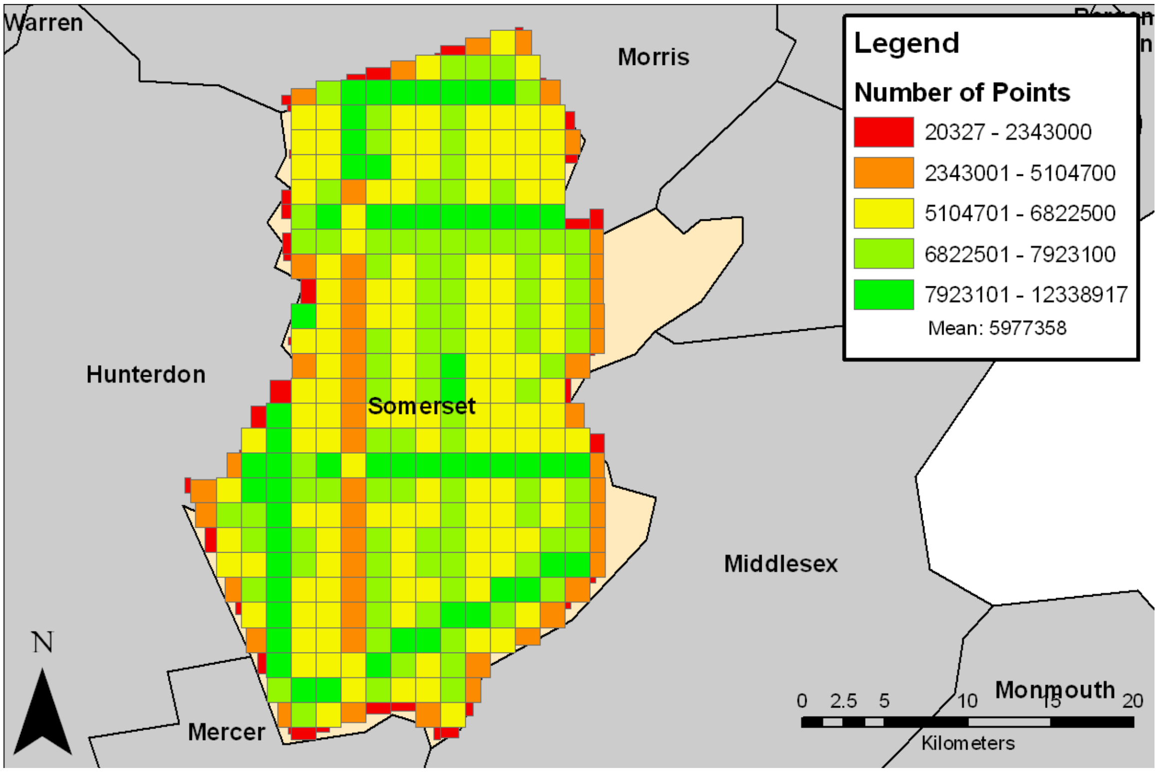


Figure 2 Number of points per tile

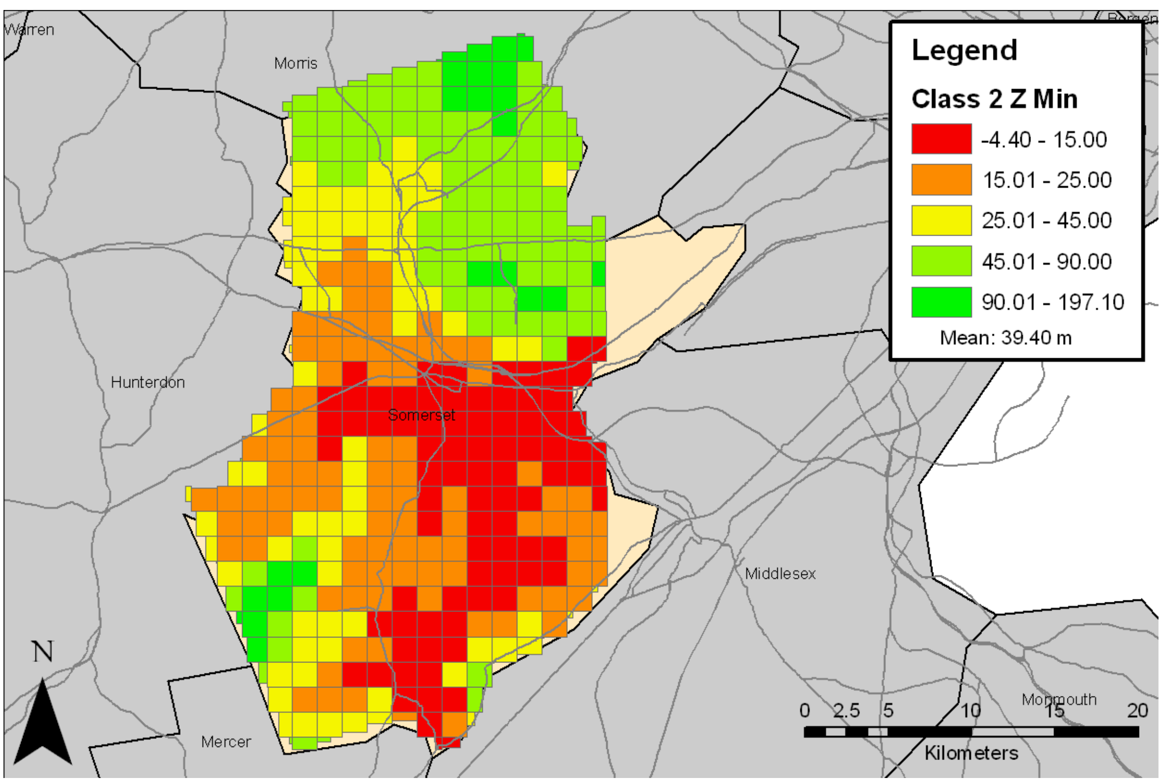


Figure 3 Minimum elevations in meters for class 2 (ground)

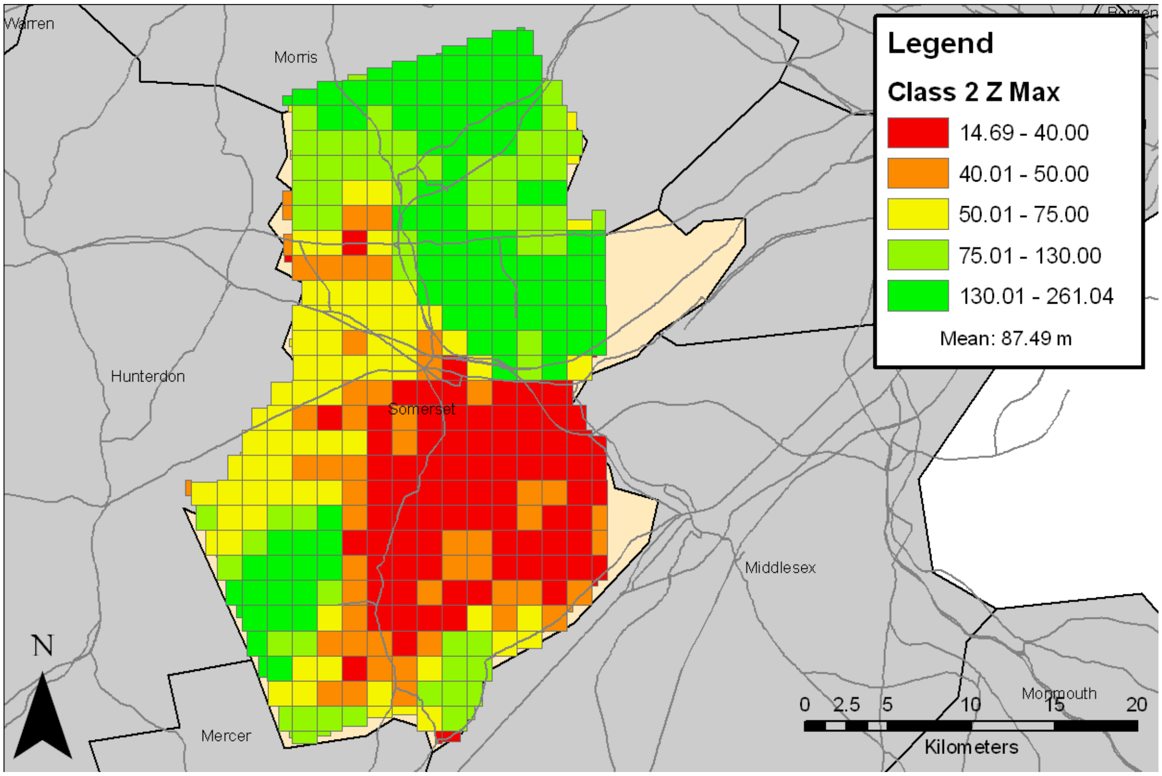


Figure 4 Maximum elevations in meters for class 2 (ground)

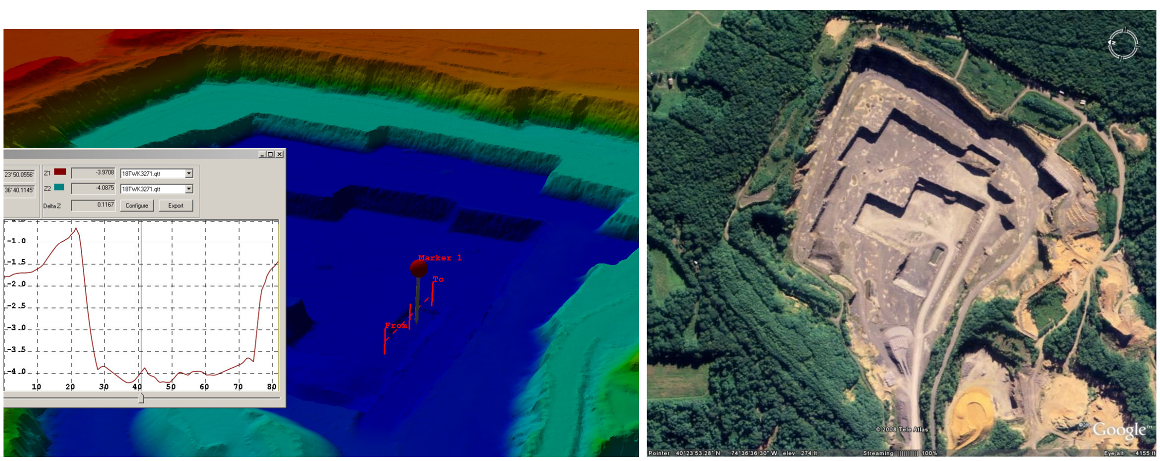


Figure 5 – 18TWK3271: Bare Earth and Google Earth Images

2.2 Quantitative assessment

2.2.1 Inventory of survey points

Dewberry used an independent verification survey from GeoMetrics to verify the accuracy of the LiDAR data.

To satisfy FEMA Guidelines and Specifications for Flood Hazard Mapping Partners (Section A.6.4 of Appendix A) a minimum of 20 checkpoints per land cover representative of the floodplain should be surveyed. In this project area four land cover types were considered representative:

1. Open bare-earth terrain – sand, dirt, rock, short grass (less than 0.5 feet)
2. Weeds and Crop – tall grass, crops, small bushes (between 1 ft – 5 ft)
3. Forested areas – deciduous trees (greater than 5 ft)
4. Urban – paved streets, parking lots, areas of buildings

As shown in Figure 6, the checkpoints were distributed evenly throughout the project area. In order to comply with FEMA standards Medium Vegetation and Forest were kept as separate classes and then combined for the USGS analysis where only three classes were required.

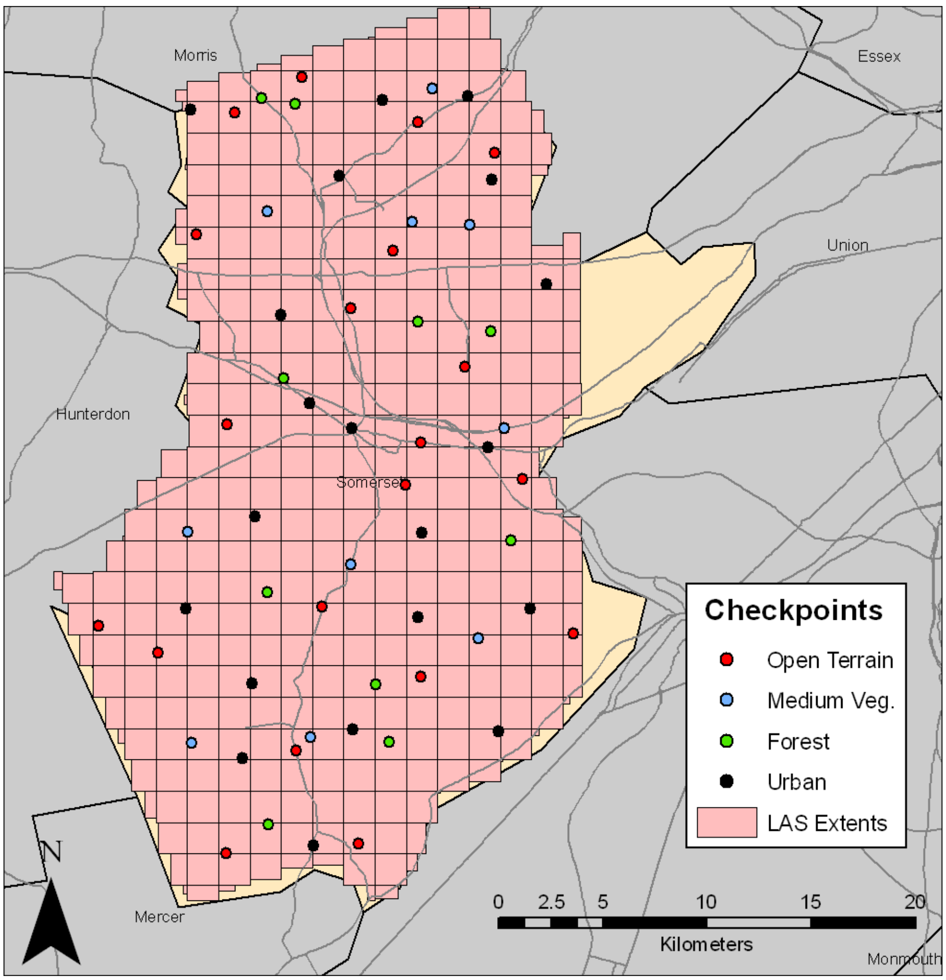


Figure 6 – Check points by land cover type

2.2.2 Vertical Accuracy Assessment Using the RMSE Methodology

The first method of testing vertical accuracy used the FEMA specifications which essentially follows the National Standard for Spatial Data Accuracy (NSSDA) procedures. The accuracy is reported at the 95% confidence level using the Root Mean Square Error (RMSE) which is valid when errors follow a normal distribution. This methodology measures the square root of the average of the set of squared differences between dataset coordinate values and coordinate values from an independent source of higher accuracy for identical points. The vertical accuracy assessment compares the measured survey checkpoint elevations with those of the TIN as generated from the bare-earth LiDAR. The survey checkpoint's X/Y location is overlaid on the TIN and the interpolated Z value is recorded. This interpolated Z value is then compared to the survey checkpoint Z value and this difference represents the amount of error between the measurements. The following tables and graphs outline the vertical accuracy and the statistics of the associated errors.

Using this method of calculating the RMSE, Somerset LiDAR meets the FEMA specifications at the 95% confidence level (all classes considered). The area exhibits outstanding results in all categories, with a consolidated RMSE of 0.077m compared with the RMSE specification of 0.185m. The data also complies to USGS requirements: vertical bare earth RMSEz of 6cm compared with the 15cm specification and vertical vegetation RMSE of 10cm compared with 27cm.

Figure 7 illustrates the distribution of the elevation differences between the LiDAR data and the surveyed points by land cover type. Errors points are well distributed around 0. It should be noted that forest and medium vegetation classes have high minimum and maximum ranges but still within acceptable ranges, we expect having higher errors in these categories because the vegetation may cause difficulties for LiDAR penetration, classification process.

Table 1 – Descriptive statistics (FEMA guidelines) by land cover category for Somerset, NJ

100 % of Totals	RMSE (m) Spec=0.185m	Mean (m)	Median (m)	Skew	Std Dev (m)	# of Points	Min (m)	Max (m)
Consolidated	0.077	0.014	0.022	-0.233	0.076	60	-0.204	0.183
Open Terrain	0.058	-0.002	0.015	-0.508	0.060	20	-0.112	0.071
Medium Veg.	0.119	0.030	0.057	-0.756	0.121	10	-0.204	0.164
Forest	0.083	0.025	0.021	0.348	0.083	10	-0.098	0.183
Urban	0.063	0.017	0.023	-0.310	0.062	20	-0.108	0.114

Table 2 - Descriptive statistics by Bare Earth or Vegetated Surfaces (USGS Specs) for Somerset, NJ

	RMSE (m) Spec=0.27m	Mean (m)	Median (m)	Skew	Std Dev (m)	# of Points	Min (m)	Max (m)
Vegetation	0.102	0.028	0.036	-0.445	0.101	20	-0.204	0.183

	RMSE (m) Spec=0.15m	Mean (m)	Median (m)	Skew	Std Dev (m)	# of Points	Min (m)	Max (m)
Bare Earth	0.061	0.008	0.019	-0.353	0.061	40	-0.112	0.114

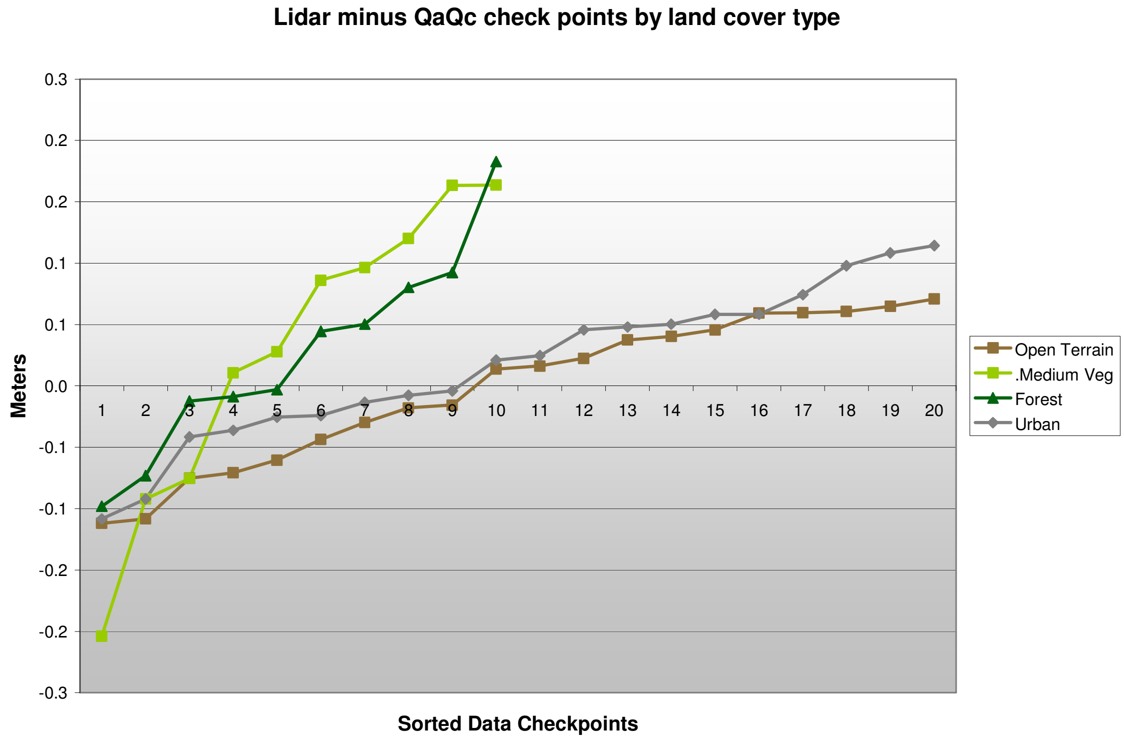


Figure 7 - Somerset County, NJ; Elevation differences between the interpolated LiDAR and the surveyed QAQC checkpoints

2.2.3 Vertical Accuracy Assessment Using the NDEP Methodology

The RMSE method assumes that the errors follow a normal distribution, and experience has shown that this is not always the case as vegetation and manmade structures can limit the ground detection causing errors greater than in unobstructed terrain. The NDEP methodology therefore assumes that the data does not follow a normal distribution and tests the open terrain (bare-earth ground) separately from other ground cover types.

The *Fundamental Vertical Accuracy* (FVA) at the 95% confidence level equals 1.96 times the RMSE in open terrain only (as previously explained: the RMSE methodology is appropriate in open terrain). *Supplemental Vertical Accuracy* (SVA) at the 95% confidence level utilizes the 95th percentile error individually for each of the other land cover categories, which may have valid reasons (e.g. problems with vegetation classification) why errors do not follow a normal distribution. Similarly the *Consolidated Vertical Accuracy* (CVA) at the 95% confidence level utilizes the 95th percentile error for all land cover categories combined. This NDEP methodology is used on 100% of the checkpoints.

The target objective for this project was to achieve bare-earth elevation data with an accuracy equivalent to 2 ft contours, which equates to an RMSE of 0.61 m when errors follow a normal distribution. With these criteria, the Fundamental Vertical Accuracy of 1.19 m must be met. Furthermore, it is desired that the Consolidated Vertical Accuracy and each of the Supplemental Vertical Accuracies also meet the 1.19 m criteria to ensure that elevations are also accurate in vegetated areas. As summarized in Table 3, this data:

- Does satisfy the NDEP's mandatory Fundamental Vertical Accuracy criteria for 2 ft contours.
- Does satisfy the NDEP's targeted Supplemental Vertical Accuracy criteria for 2 ft contours.
- Does satisfy the NDEP's mandatory Consolidated Vertical Accuracy criteria for 2 ft contours.

Table 3 – Somerset, NJ; accuracy using NDEP methodology

Land Cover Category	# of Points	FVA — Fundamental Vertical Accuracy (RMSEz x 1.9600) Spec=0.363 m	CVA — Consolidated Vertical Accuracy (95th Percentile) Spec=0.363m	SVA — Supplemental Vertical Accuracy (95th Percentile) Target=0.363 m
Consolidated	60		0.163	
Open Terrain	20	0.114		0.108
Medium Veg.	10			0.186
Forest	10			0.145
Urban	20			0.109

2.2.4 Horizontal assessment

Typically horizontal accuracy in LiDAR is implied since it is not explicitly tested. It is however tested during the calibration of the LiDAR system and is verified in the daily check flights by comparing parallel and perpendicular flights over a test area. To ensure no horizontal errors occur, we tested the data by comparing the LiDAR data to orthophotos. Of course, this will only inform us about the relative accuracy of the Lidar, any discrepancy between these 2 sources will not give an accurate value of the hypothetical horizontal displacement.

For the review, 5 orthophotos were downloaded from the State of New Jersey Office of Information Technology, Office of Geographic Information Systems[*]. Their Horizontal Positional Accuracy Report is:

> "Orthophotography has a +/- 4.0 ft. horizontal accuracy at 95% confidence level, National Standard for Spatial Data Accuracy (NSSDA), for a 1.0 foot Ground Resolution Distance (GRD)."

Using these aerial orthophotos, analysts digitized road intersections and other objects easily seen in the LiDAR intensity in 2 locations in each tile. The vector lines were then overlaid on the masspoints displayed with the intensity. Screen shots of the overlay are available in Appendix C.

By visual interpretation we were able to determine that the LiDAR points match the orthophoto, which comforts our judgment that the horizontal accuracy shall meet 0.5-m

[*] http://njgin.nj.gov/OIT_IW/index.jsp

RMS. To reiterate this is not a valid statistical test but an indirect verification of the horizontal accuracy of the data.

2.2.5 Quantitative Accuracy Conclusion

Utilizing both methods of vertical accuracy testing, LiDAR data meets and exceeds all specifications. The Lidar horizontal coordinates perfectly agree with reference orthophotos.

2.3 Qualitative assessment

2.3.1 Protocol

The goal of this qualitative review is to assess the continuity and the level of cleanliness of the bare earth product and to ensure its conformance to support the intended final product. The following acceptance criteria were reviewed:

- If the density of point is homogeneous, correctly supported by flightline overlap and sufficient to meet the user needs.
- If the ground points have been correctly classified (no manmade structures and vegetation remains, no gap except over water bodies),
- If the ground surface model exhibits a correct definition (no aggressive classification, no over-smoothing, no inconsistency in the post-processing), in a context of flood modeling, special attention is given to the stream channels,
- If no obvious anomalies due to sensor malfunction or systematic processing artifact is present (data holidays, spikes, divots, ridges between tiles, cornrows…).

Dewberry analysts, experienced in evaluating LIDAR data, performed a visual inspection of the bare-earth digital elevation model (bare-earth DEM). LiDAR mass points were first gridded with a grid distance of 2x the full point cloud resolution. Then, a triangulated irregular network (TIN) was built based on this gridded DEM and displayed as a 3D surface. A shaded relief effect was applied which enhances 3D rendering. The software used for visualization allows the user to navigate, zoom and rotate models and to display elevation information with an adaptive color coding in order to better identify anomalies.
One of the variables established when creating the models is the threshold for missing data. For each individual triangle, the point density information is stored; if it meets the threshold, the corresponding surface will be displayed in green, if not it will be displayed in red (see Figure 8).

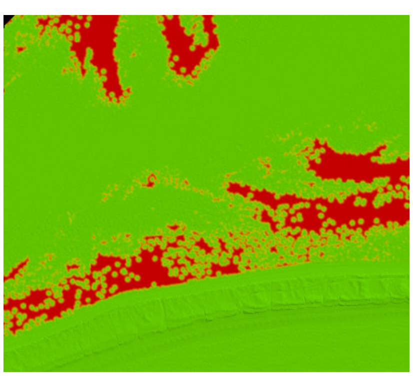


Figure 8 – Ground model with density information (red means no data)

The first step of our qualitative workflow was to verify the point distribution by systematically loading a percentage of the tiles as mass points colored by class or by flightline. This particular type of display helps us visualize and better understand the scan pattern, the flight line orientation, flight coverage, and gives an additional confirmation that all classes are present and seem to logically represent the terrain.

The second step was to verify data completeness and continuity using the bare-earth DEM with density information, displayed at a macro level. If, during this macro review of the ground models, we find potential artifacts or large voids, we use the digital surface model (DSM) based on the full point cloud including vegetation and buildings to help us better pinpoint the extent and the cause of the issue. Moreover, the intensity information stored in the LiDAR data can be visualized over this surface model, helping in interpretation of the terrain.

The process of importing, comparing and analyzing these two later types of models (DSM with intensity and raw mass point), along with cross section extraction, surface measurements, density evaluation, constitutes our micro level of review.

2.3.2 Quality report

Our Qualitative review was to perform a macro visual inspection of all the tiles. Additionally we reviewed 10% of the data for the scanning and flightline consistency.
The first submission of LiDAR was missing two tiles with the project boundary. The second submission contained those previously missing tiles and also corrected some misclassification issues in the first delivery.

Our professional judgment is that the majority of the bare earth models are of good quality (as seen in Figure 9) but some minor issues do exist. Dewberry did find errors in the data as outlined in the text and images below (contact sheets of all the errors found during the review are given in Appendix A). The comments we had included poor penetration of the LiDAR beam in vegetation, aggressive classification, divots, noise, and building artifacts.

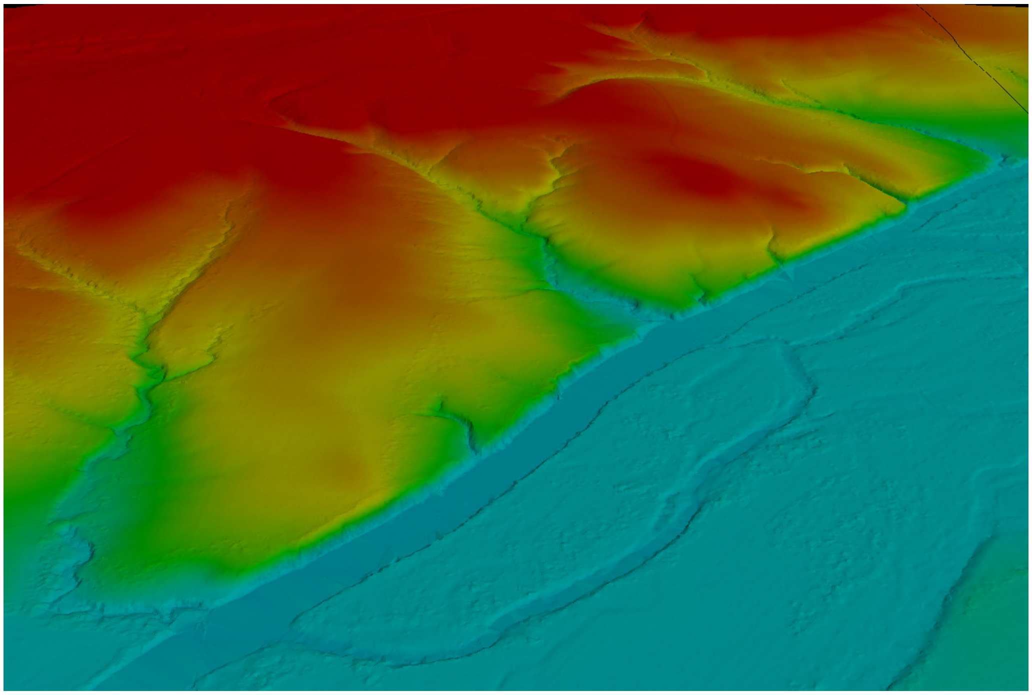
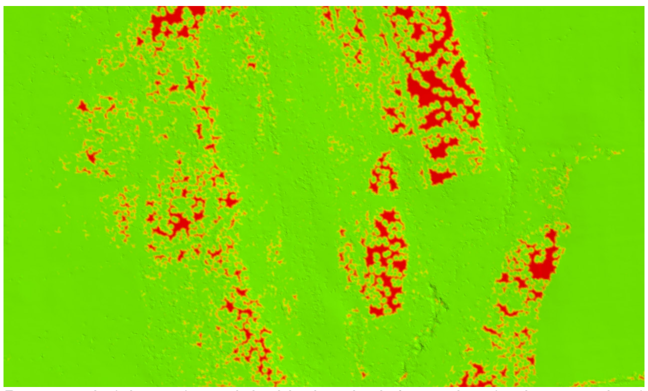


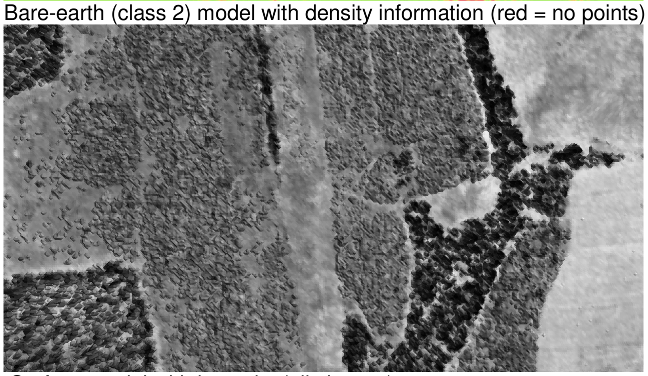
Figure 9 – Good example of the quality of the bare-earth

➢ Poor LiDAR penetration

A problem that we often found is patches with lower density of ground points. When the vegetation is very dense, the LiDAR may not penetrate the canopy all the way to the ground, therefore only a few ground points remain after classification of the vegetation. Nevertheless, as soon as a few points are present, a 3D model can be built with an acceptable reliability, especially in flat areas. However, the definition of the surface is often of poorer quality; this is illustrated in Figure 10. This especially occurs in coniferous forest.



Bare-earth (class 2) model with density information (red = no points)



Surface model with intensity (all classes)

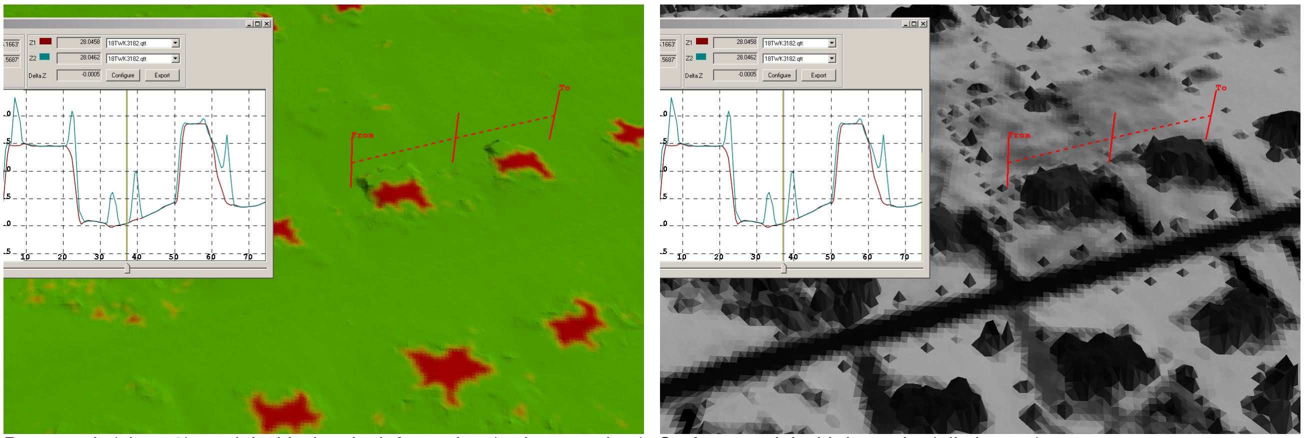
Ortho Photo in leaf off condition: the arrow point is in a coniferous forest

Figure 10 – 18TWK2897: poor Lidar penetration in dense vegetation (coniferous forest)

➢ Misclassification

- Building Artifacts

  Some portions of buildings remain classified as ground. Figure 11 is an example of this error and the remaining screenshots are in the Appendix A.

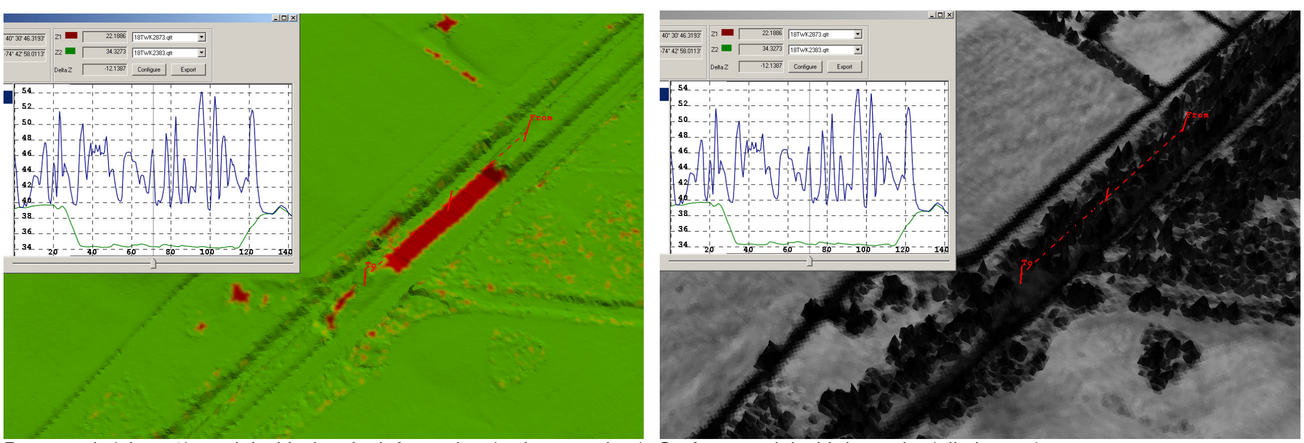


Bare-earth (class 2) model with density information (red = no points), Surface model with intensity (all classes)

Figure 11 – 18TWK3182: Building artifacts

- Aggressive classification

  The LiDAR data has less than 10 aggressive classification issues similar to Figure 12. Sections of road edges are inconsistently erased from the ground.

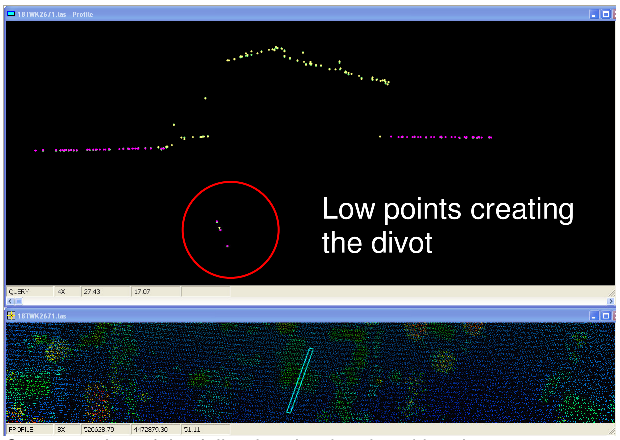


Bare-earth (class 2) model with density information (red = no points), Surface model with intensity (all classes)

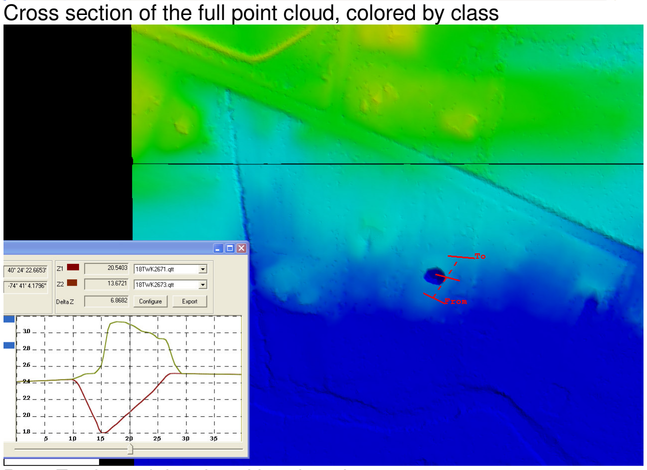
Figure 12 – 18TWK2383: aggressive classification

➢ Divots

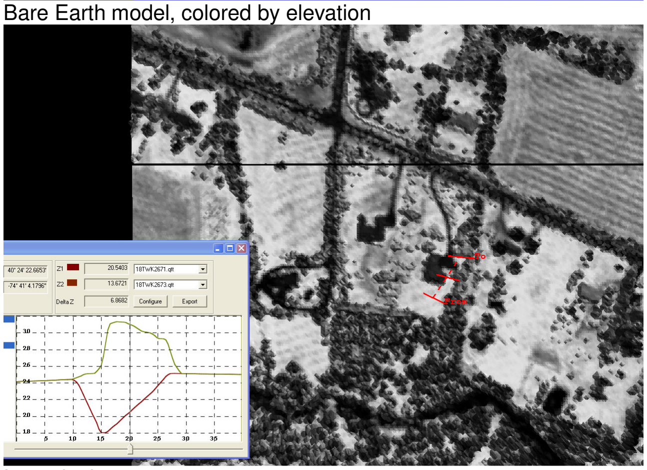
There were less than 5 small divots within the project area. These can be seen in Appendix A. The elevation of a LiDAR point is set by the time it takes the pulse to return to the sensor. The divot in Figure 13 was likely to be created by a pulse bouncing off of an object (house wall) and taking longer to return to the sensor and thus having a lower elevation.



Cross section of the full point cloud, colored by class



Bare Earth model, colored by elevation



Intensity Image

Figure 13 – 18TWK2671, divot

➢ Noise

The noise in Somerset remains a small issue. In some areas the ground appears more noisy because of the overlapping of two flights. Other more prevalent reasons for noise include heavy vegetation; both types of noise are shown in Figure 13.

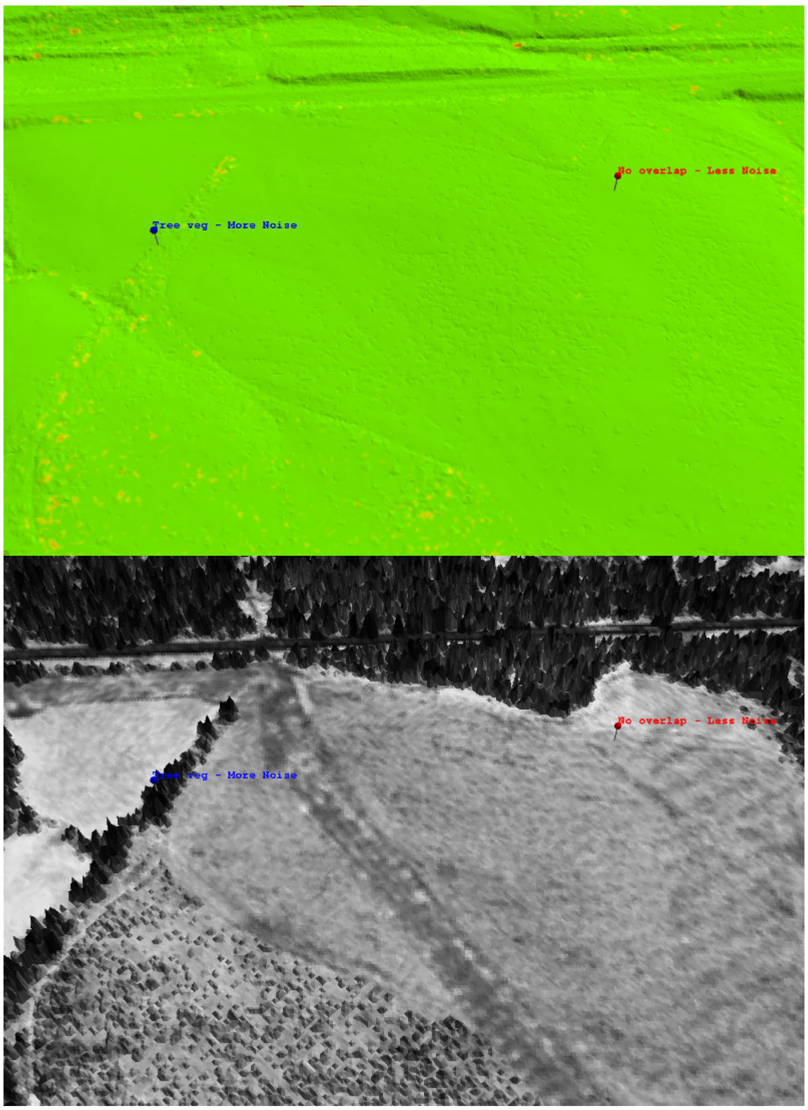


Figure 14 – 18TWK2583: Ground and Intensity images displaying different noise types

In summary, the types of issues more frequently encountered are:

- Poor LiDAR penetration resulting in a noisy surface
- Classification issues (building artifacts, aggressive classification, divots)

It should be noted that these data may have unidentified errors at a local scale as we are not performing an exhaustive review at micro level.

To reiterate, these errors were minor. Dewberry believes that the overall quality of the data is satisfactory. It also may require slight modifications to fit specific application needs. However, this data will meet the needs of the general users of elevations data.

3 Conclusion

Even though there were minor issues that data exhibits good detail overall. The data accuracy standards for artifact/feature removal were as follows:

95% of artifacts or more removed depending on terrain and vegetation
98% of outliers removed
97% of all vegetation removed and
99% of all buildings removed

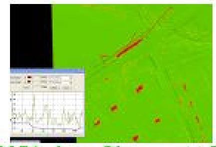
Based on our review all of these requirements were met and surpassed. In total, the data exceeds the quantitative accuracy requirements and the level of cleanliness for the bare-earth terrain is of satisfactory quality.

Appendix A Screen shot of the issues and comments

Aggressive Classification


18TWK1785_aggrclass_qttground.bmp


18TWK1785_aggrclass_qttINT.bmp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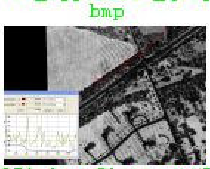
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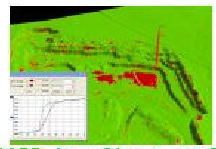
18twk2271_AggrClass_qttLas.bmp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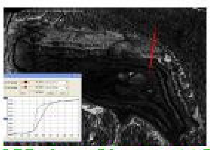
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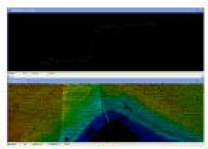
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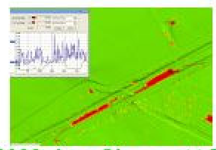
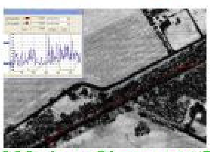
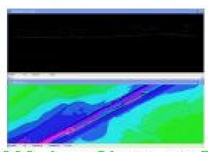
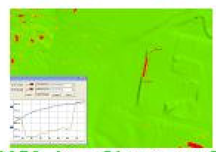
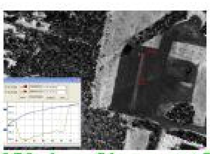

18twk2383_AggrClass_qttGnd.bmp

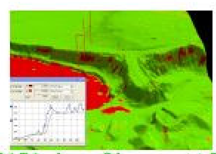

18twk2383_AggrClass_qttInt.bmp

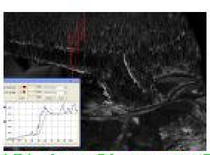

18twk2383_AggrClass_qttLas.bmp


18twk2873_AggrClass_qttGnd.bmp


18twk2873_AggrClass_qttInt.bmp


18twk2873_AggrClass_qttLas.bmp


18twk3171_AggrClass_qttGnd.bmp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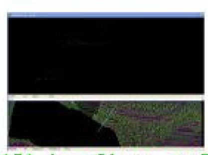
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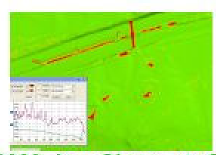
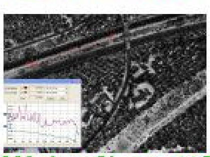

18twk3298_AggrClass_qttGnd.bmp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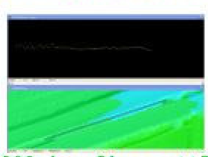
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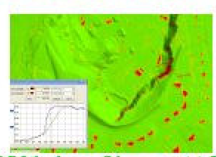
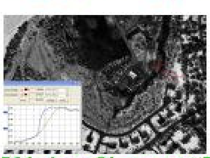
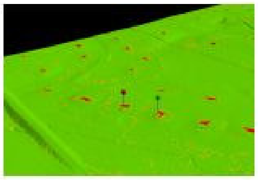

18twl3506_AggrClass_qttGnd.bmp

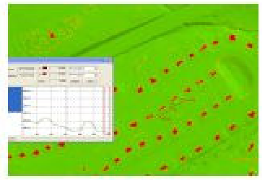

18twl3506_AggrClass_qttInt.bmp

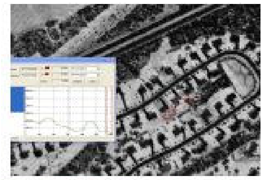

18twl3506_AggrClass_qttLas.bmp

Building Artifacts


18twk2083_BuildingArtifact_qttGnd.bmp


18twk2083_BuildingArtifact_qttInt.bmp


18twk2288_BuildingArtifact_qttGnd.bmp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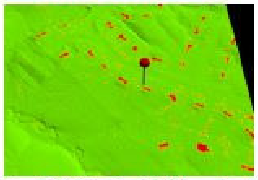
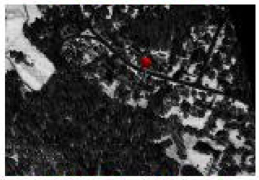
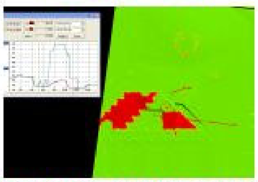
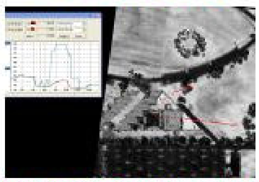

18twk2395_BuildingArtifact_qttGnd.bmp


18twk2395_BuildingArtifact_qttInt.bmp


18twk2398_BuildingArtifact_qttGnd.bmp


18twk2398_BuildingArtifact_qttInt.bmp


18twk2574_BuildingArtifact_qttGnd.bmp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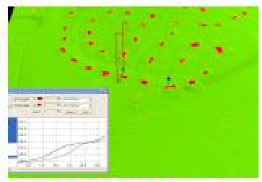
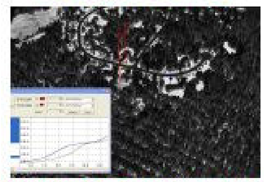
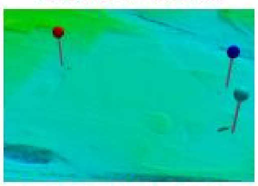
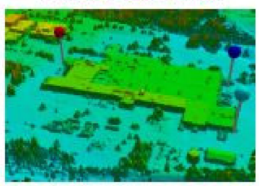

18twk2582_BuildingArtifact-deck_qttGnd.bmp

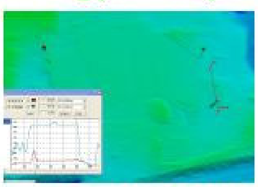

18twk2582_BuildingArtifact-deck_qttInt.bmp


18twk2594_BuildingArtifact_qttGnd.bmp

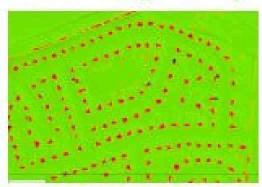

18twk2594_BuildingArtifact_qttInt.bmp


18twk2594_BuildingArtifact-Class_Las.bmp

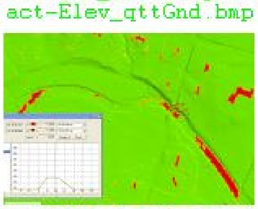

18twk2594_BuildingArtifact-Dens_qttGnd.bmp


18twk2594_BuildingArtifact-Elev_qttGnd.bmp


18twk2594_BuildingArtifact-Inten_qttInt.bmp


18twk2685_BuildingArtifact_qttGnd.bmp

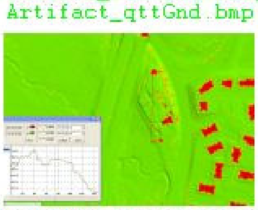

18twk2685_BuildingArtifact_qttInt.bmp


18twk2873_PartialBridgeArtifact_qttGnd.bmp


18twk2873_PartialBridgeArtifact_qttInt.bmp


18twk2895_BuildingArtifact_qttGnd.bmp


18twk2895_BuildingArtifact_qttInt.bmp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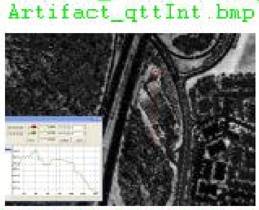
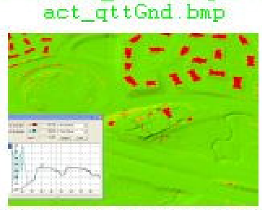
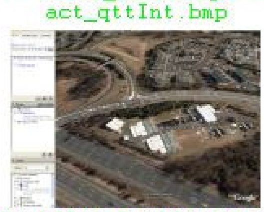
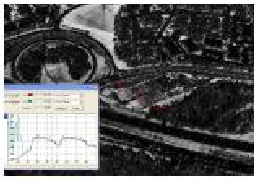

18twk2900_BuildingArtifact_qttInt.bmp

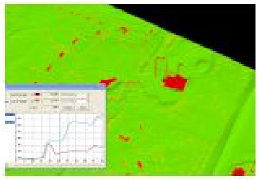

18twk2900_BuildingArtifact-ReverseAngle_qttGnd


18twk2900_BuildingArtifact-ReverseAngle_qttGoo

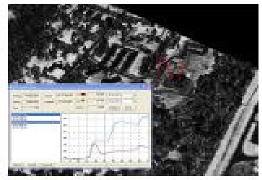
Building Artifacts



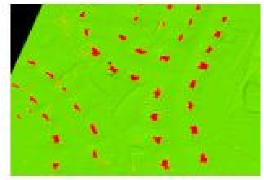
18twk2900_BuildingArtifact-ReverseAngle_qttInt.bmp



18twk2997_BuildingArtifact_qttGnd.bmp



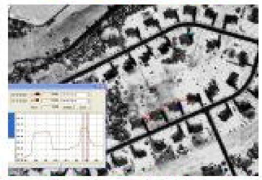
18twk2997_BuildingArtifact_qttInt.bmp



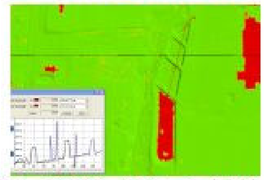
18twk3177_BuildingArtifact_qttGnd.bmp

18twk3177_BuildingArtifact_qttInt.bmp

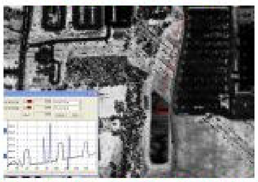
18twk3182_BuildingArtifact_qttGnd.bmp



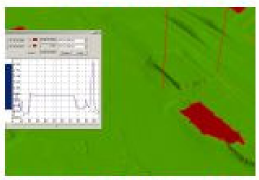
18twk3182_BuildingArtifact_qttInt.bmp



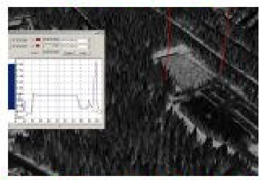
18twk3183-3185_BuildingArtifact_qttGnd.bmp



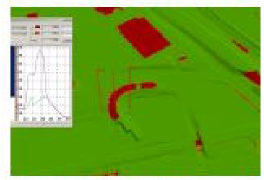
18twk3183-3185_BuildingArtifact_qttInt.bmp



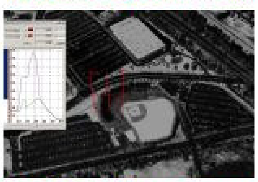
18TWK3498_buildartifact_qttground.bmp



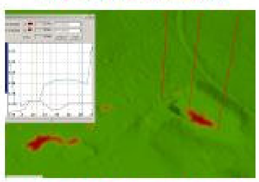
18TWK3498_buildartifact_qttINT.bmp



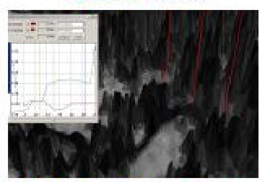
18TWK3789_buildingartifact_qttground.bmp



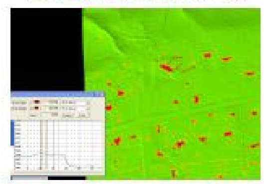
18TWK3789_buildingartifact_qttINT.bmp



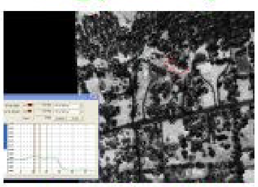
18TWK3794_buildingartifact_qttground.bmp



18TWK3794_buildingartifact_qttINT.bmp



18twk3894_BuildingArtifact_qttGnd.bmp



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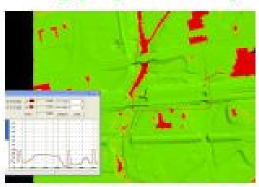
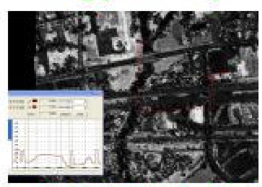
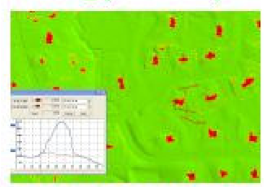


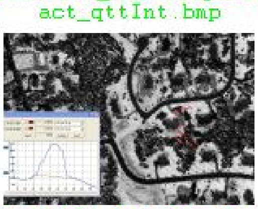
18twk4089_PartialBridgeArtifact_qttGnd.bmp



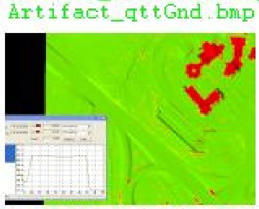
18twk4089_PartialBridgeArtifact_qttInt.bmp



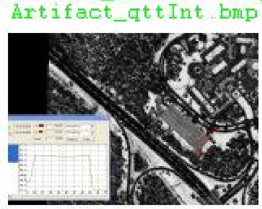
18twk4194_BuildingArtifact_qttGnd.bmp



18twk4194_BuildingArtifact_qttInt.bmp

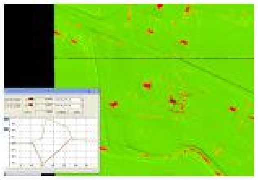


18twl2806_BuildingArtifact_qttGnd.bmp



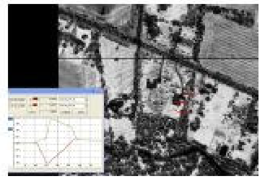
18twl2806_BuildingArtifact_qttInt.bmp

Divots



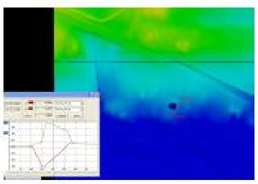
18twk2671_Divot_qttGnd.bmp

18twk2671_Divot_qttGnd_LAS.bmp

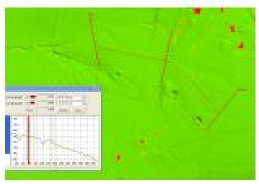


18twk2671_Divot_qttInt.bmp

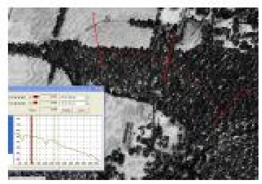
18twk2671_Divot-class_qttLas.bmp



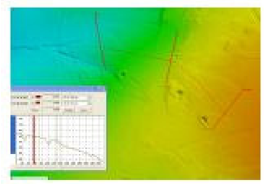
18twk2671_Divot-elev_qttGnd.bmp



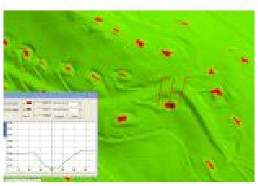
18twk3274_Divot_qttGnd.bmp



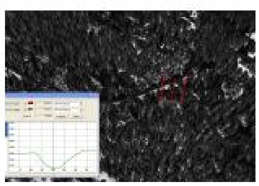
18twk3274_Divot_qttInt.bmp



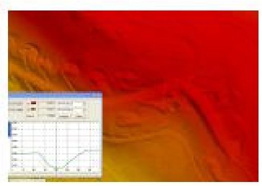
18twk3274_Divot-elev_qttGnd.bmp



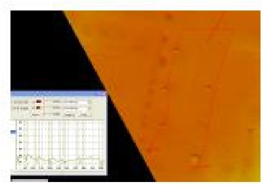
18twk3297_Divot_qttGnd.bmp



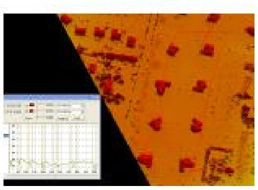
18twk3297_Divot_qttInt.bmp



18twk3297_Divot-elev_qttGnd.bmp

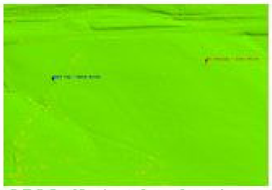


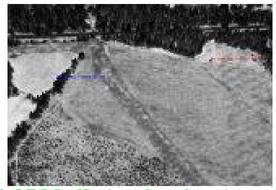
18twk4080_Divot-elev_qttGnd.bmp



18twk4080_Divot-elev_qttInt.bmp

Noise


18twk2583_NoiseAnalysis_qttGnd.bmp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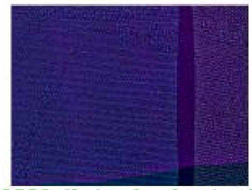
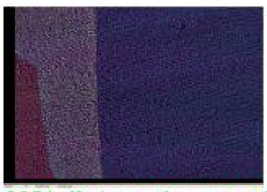

18twk2583_NoiseAnalysis-SourceID_qttLas.bmp


18twk2585_Noise_qttGnd.bmp


18twk2585_Noise_qttInt.bmp


18twk2585_Noise-SourceID_qttLas.bmp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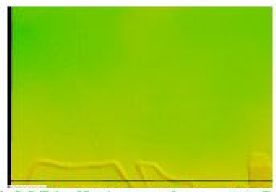
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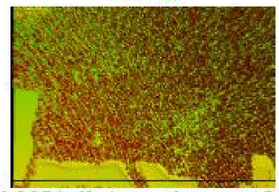
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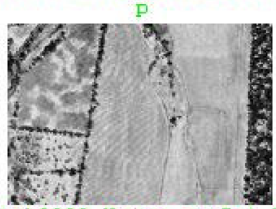
18twk2888_Noise_qttGnd.bmp

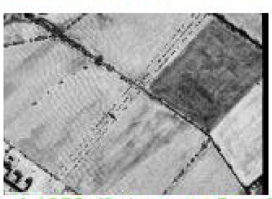

18twk2888_Noise_qttInt.bmp


18twk2888_Noise-SourceID_qttLas.bmp


18TWK3574_noise_qttground.bmp


18TWK3574_noise_qttINT.bmp

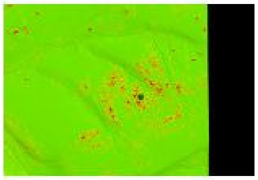

18twk4079_Noise_qttGnd.bmp


18twk4079_Noise_qttInt.bmp


18twk4079_Noise-class_qttLas.bmp


18twk4079_Noise-elev_qttGnd.bmp

PoorLidarPenetration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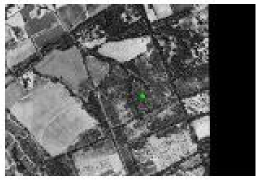
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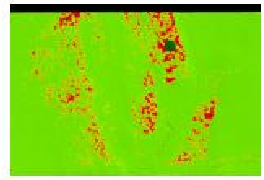
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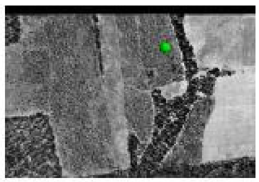
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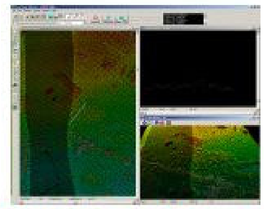
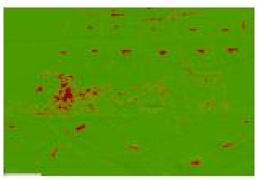
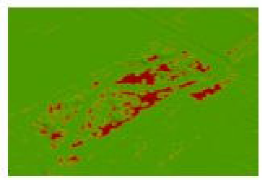

18TWK1985_poorLidarpenetr_LAS.bmp


18TWK1985_poorLidarpenetr_qttground.bmp


18TWK1985_poorLidarpenetr_qttINT.bmp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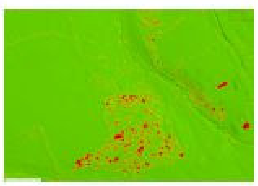
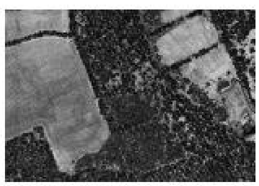
18TWK2073_poorLidarpenetr_qttINT.bmp


18TWK2079_PoorLidarPenet1_qttGnd.bmp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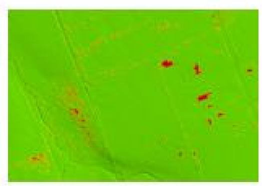
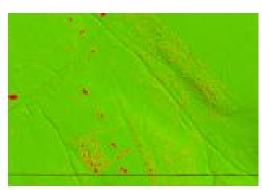

18TWK2079_PoorLidarPenet2_qttGnd.bmp


18TWK2079_PoorLidarPenet2_qttInt.bmp


18TWK2079_poorLidarpenetr_qttground.bmp


18TWK2079_poorLidarpenetr_qttINT.bmp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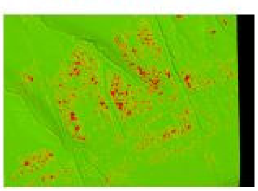
18TWK2080_PoorLidarPenet1_qttInt.bmp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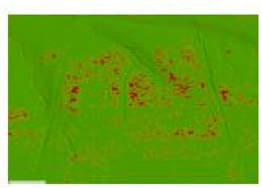
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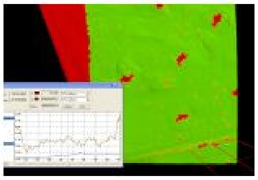
18TWK2080_poorLidarpenetre_qttINT.bmp

PoorLidarPenetration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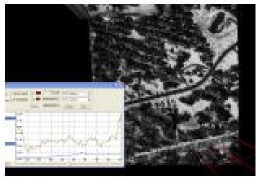
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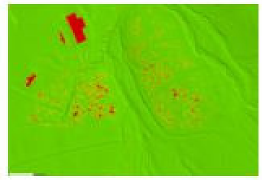
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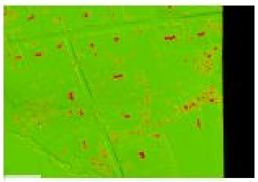
18twk2280_PoorLidarPene t_qttInt.bmp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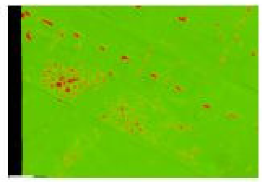
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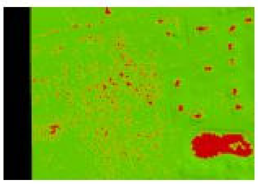
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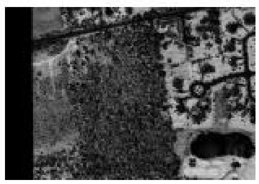
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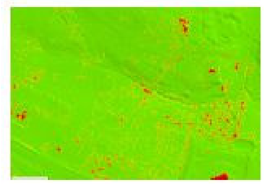
18twk2395_PoorLidarPene t_qtcGnd.bmp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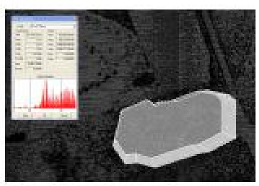
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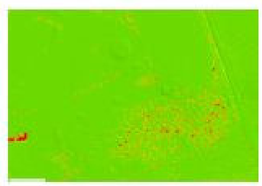
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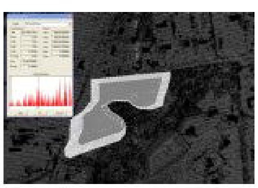
18twk2398_PoorLidarPene t_qttInt.bmp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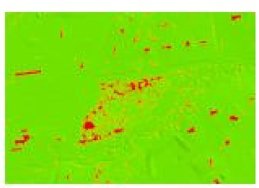
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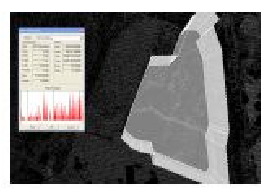
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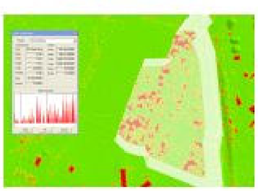
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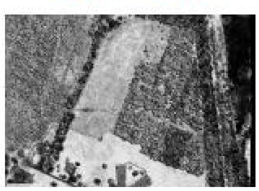
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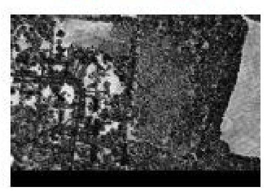
18twk2671_PoorLidarPene t_qttGnd.bmp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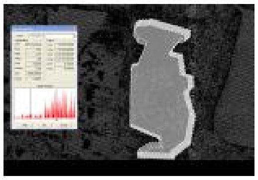
PoorLidarPenetration



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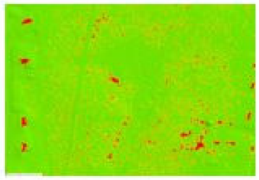

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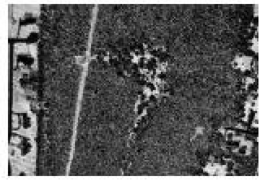

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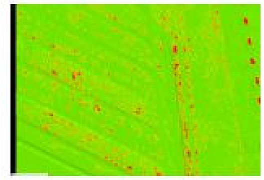

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18twk2880_PoorLidarPene
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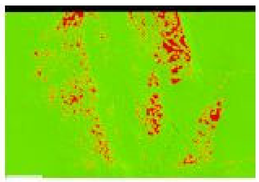

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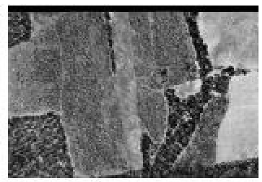

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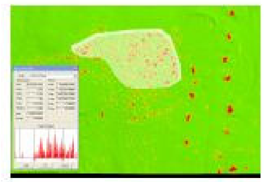

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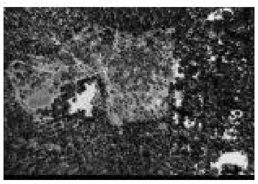

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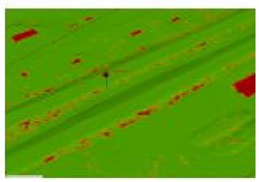

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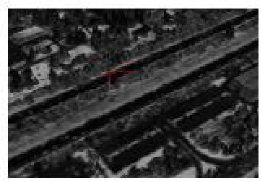

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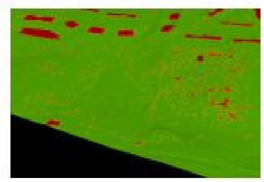
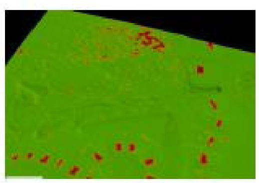


18TWK3500_poorLidarpene
tr_qttground.bmp

18TWK3500_poorLidarpene
tr_qttINT.bmp



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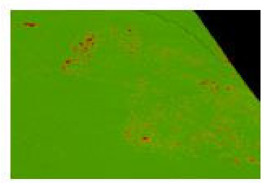

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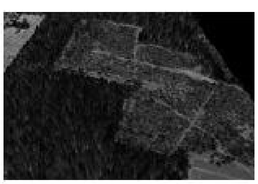

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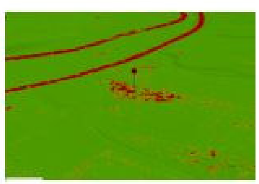

18TWK3579_poorLidarpen_
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18TWK3579_poorLidarpen_
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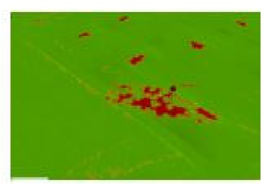

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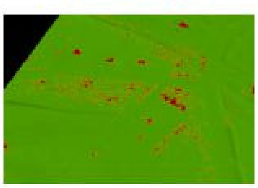

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18TWK3776_poorLidarpen_
qttINT.bmp

18TWK3776_poorLidarpen_
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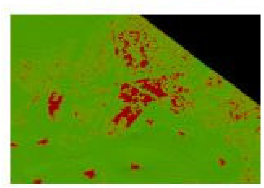

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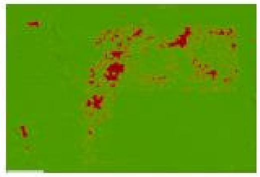
PoorLidarPenetration

18TWK3777_poorLidarpen_qttINT.bmp



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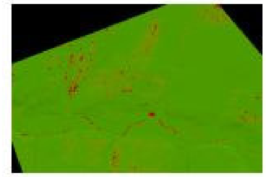
18TWK3782_poorLidarpen_qttINT.bmp



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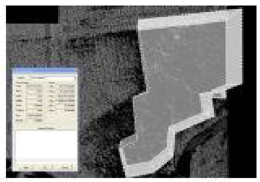
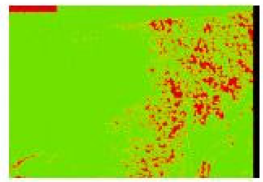
18TWK3879_poorLidarpenetr_qttINT.bmp



18twk4000_PoorLidarPenet1_qtcLas.bmp



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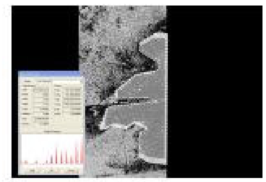

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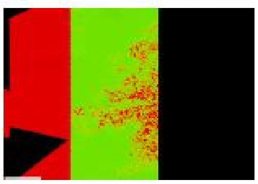

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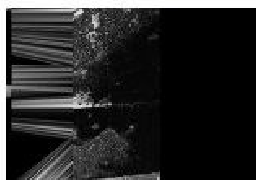
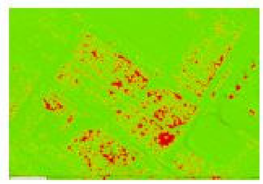
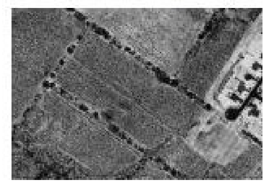


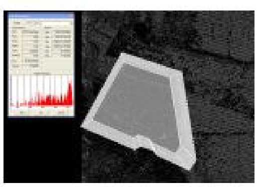
18twk4000_PoorLidarPenet2_qttInt.bmp



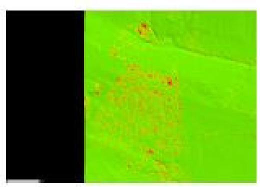
18twk4079_PoorLidarPenet_qttGnd.bmp



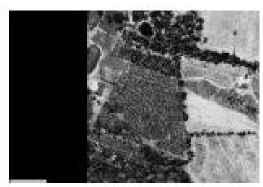
18twk4079_PoorLidarPenet_qttInt.bmp



18twl2803_PoorLidarPenet_qtcLas.bmp



18twl2803_PoorLidarPenet_qttGnd.bmp



18twl2803_PoorLidarPenet_qttInt.bmp

Appendix B Checkpoints

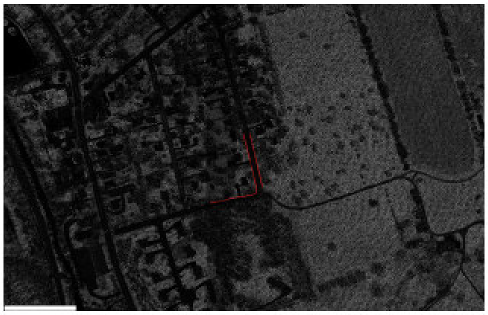
pointNo	easting	northing	elevation	zLidar	LandCoverType	DeltaZ	AbsDeltaZ
G004	538245.595	4505047.934	123.347	123.235	Open Terrain	-0.112	0.112
G005	533353.536	4500348.239	117.181	117.073	Open Terrain	-0.108	0.108
G009	536833.037	4494778.121	94.901	94.826	Open Terrain	-0.075	0.075
G014	519283.633	4482416.955	45.338	45.267	Open Terrain	-0.071	0.071
G018	542008.260	4482045.135	38.245	38.185	Open Terrain	-0.060	0.060
G002	528987.376	4508676.119	114.034	113.990	Open Terrain	-0.044	0.044
G007	525436.288	4492031.658	57.402	57.372	Open Terrain	-0.030	0.030
G011	539568.651	4489423.808	18.336	18.318	Open Terrain	-0.018	0.018
G019	531718.237	4471967.933	18.940	18.924	Open Terrain	-0.016	0.016
G017	534707.614	4479970.012	34.025	34.039	Open Terrain	0.014	0.014
G006	523963.658	4501132.643	48.463	48.479	Open Terrain	0.016	0.016
G003	534550.874	4506498.240	97.132	97.154	Open Terrain	0.022	0.022
G013	529977.282	4483312.794	25.854	25.891	Open Terrain	0.037	0.037
G016	528723.533	4476428.620	32.359	32.399	Open Terrain	0.040	0.040
G015	522127.135	4481122.397	82.233	82.279	Open Terrain	0.046	0.046
G020	525384.018	4471494.293	27.366	27.425	Open Terrain	0.059	0.059
G001	525791.456	4506960.368	141.000	141.060	Open Terrain	0.060	0.060
G012	533949.290	4489137.931	14.392	14.453	Open Terrain	0.061	0.061
G008	531366.599	4497609.173	81.003	81.068	Open Terrain	0.065	0.065
G010	534714.141	4491176.490	28.455	28.526	Open Terrain	0.071	0.071
W006	527332.849	4502250.489	50.788	50.584	Medium Veg.	-0.204	0.204
W010	538693.427	4491848.243	41.459	41.367	Medium Veg.	-0.092	0.092
W004	537045.083	4501588.927	72.882	72.807	Medium Veg.	-0.075	0.075
W018	537444.461	4481795.977	30.261	30.272	Medium Veg.	0.011	0.011
W005	534304.560	4501740.334	74.920	74.948	Medium Veg.	0.028	0.028
W015	523725.846	4476782.831	123.837	123.923	Medium Veg.	0.086	0.086
W014	523550.167	4486887.720	48.183	48.279	Medium Veg.	0.096	0.096
W016	529405.831	4477091.270	26.739	26.859	Medium Veg.	0.120	0.120
W012	531338.474	4485345.021	24.097	24.260	Medium Veg.	0.163	0.163
W003	535234.585	4508137.958	161.260	161.424	Medium Veg.	0.164	0.164
F009	538053.707	4496520.392	133.151	133.053	Forest	-0.098	0.098
F001	527075.128	4507673.016	110.351	110.278	Forest	-0.073	0.073
F020	527391.626	4472878.323	19.123	19.111	Forest	-0.012	0.012
F013	527327.124	4484012.564	36.511	36.502	Forest	-0.009	0.009
F002	528687.853	4507387.163	64.619	64.616	Forest	-0.003	0.003
F017	532519.136	4479593.753	35.451	35.496	Forest	0.044	0.044
F019	533173.671	4476820.543	20.234	20.284	Forest	0.050	0.050
F007	528119.593	4494236.533	26.373	26.453	Forest	0.080	0.080
F011	539011.121	4486464.904	26.148	26.241	Forest	0.093	0.093
F008	534552.420	4496949.764	100.709	100.892	Forest	0.183	0.183
U009	540726.785	4498756.071	100.947	100.839	Urban	-0.108	0.108
U003	536965.877	4507739.461	119.053	118.961	Urban	-0.092	0.092
U014	523435.505	4483238.460	49.023	48.981	Urban	-0.042	0.042

U006	528004.250	4497257.846	31.820	31.784	Urban	-0.036	0.036
U018	538436.723	4477356.646	32.884	32.859	Urban	-0.025	0.025
U004	538075.784	4503736.590	95.759	95.735	Urban	-0.024	0.024
U007	529378.762	4493041.016	50.498	50.485	Urban	-0.014	0.014
U008	531403.789	4491839.203	34.731	34.723	Urban	-0.008	0.008
U010	537891.811	4490930.542	15.841	15.837	Urban	-0.004	0.004
U016	531458.439	4477423.963	31.403	31.424	Urban	0.021	0.021
U012	534749.598	4486872.461	10.613	10.638	Urban	0.025	0.025
U005	530778.719	4503934.298	50.251	50.297	Urban	0.046	0.046
U001	523695.123	4507116.396	71.654	71.702	Urban	0.048	0.048
U011	539924.963	4483216.604	34.613	34.663	Urban	0.050	0.050
U015	526622.082	4479656.718	35.082	35.140	Urban	0.058	0.058
U019	529566.638	4471900.691	35.411	35.469	Urban	0.058	0.058
U020	526171.704	4476056.143	33.583	33.657	Urban	0.074	0.074
U013	526752.905	4487636.363	42.769	42.867	Urban	0.098	0.098
U017	534558.375	4482815.342	19.399	19.507	Urban	0.108	0.108
U002	532860.984	4507573.330	207.256	207.370	Urban	0.114	0.114

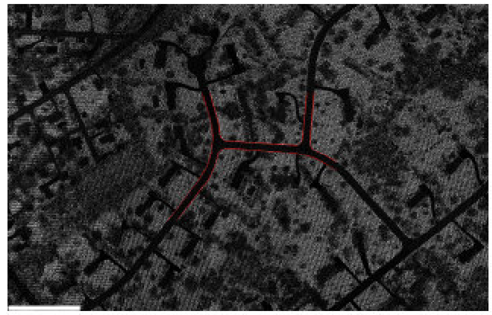
Appendix C Horizontal relative accuracy

Validation of the Lidar masspoints with intensity against vector lines digitized on orthophoto:

Horizontal accuracy checks



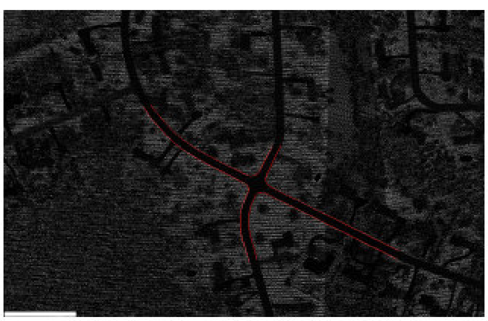
g6c16_18twl2806_roadedge.bmp



g6c16_18twl2807_roadedge.bmp

g8b12_18twk3489_roadedge.bmp

g8b12_18twk3491_roadedge.bmp



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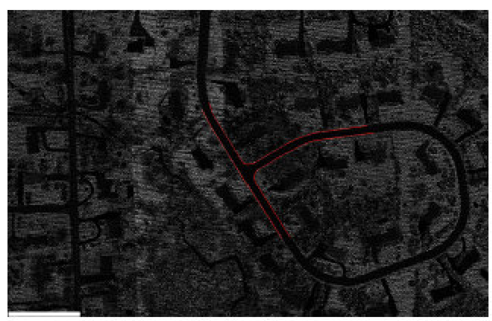
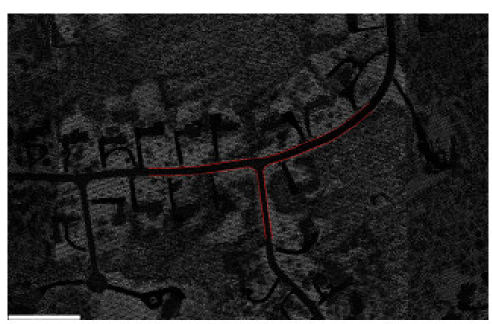


g8c14_18twk2583_roadedge.bmp

h7d9_18twk4197_buildingfootprint.bmp



h7d9_18twk4197_roadedge.bmp

Horizontal accuracy checks


h8d13_18twk4182_roadedge.bmp


h8d13_18twk4183_roadedge.bmp